On the biomechanical significance of inter-lamellar interfaces in the intervertebral disc

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Introduction

The intervertebral disc (IVD) is a unique soft tissue structure which provides structural support and flexibility in the axial skeleton of vertebrates. From a structural perspective, the disc behaves somewhat like a thick walled pressure vessel, where the walls are comprised of a series of composite annular rings (lamellae). However, a prior study (Marchand and Ahmed, 1990) found a high proportion of circumferentially discontinuous lamellae in human lumbar IVDs. The presence of these discontinuities raises important structural questions, because discontinuous lamellae cannot withstand high nucleus pressures via the generation of circumferential (hoop) stress. A possible alternative mechanism may be that inter-lamellar cohesion allows shear stress transfer between adjacent annular layers. The aim of the present study was therefore to investigate the importance of inter-lamellar shear resistance in the intervertebral disc.

Methods

Polarised light microscopy (Fig1) was used to image and measure the transverse plane dimensions of IVD annular layers in a single bovine tail IVD, and a micro-structural FE model comprising 1/8 of the volume of the disc annulus fibrosus was developed using these dimensions and appropriate symmetry considerations in ABAQUS (v6.11, Dassault Systèmes, Paris, France). Each modelled lamellar layer comprised a hyperelastic ground substance with embedded collagen fibre bundles. The model was loaded in uniaxial compression (Fig 2) and a range of inter-lamellar shear conditions were simulated to assess the importance of shear resistance on predicted IVD stiffness. For model validation, physical compression tests were performed on four other bovine tail IVDs both before and after denucleation (loading rate 100N/min to a maximum load of 400N).

Results

The polarised light micrograph revealed 15,11,15 and 16 lamellae through the annulus thickness at the dorsal, ventral, left and right locations respectively, and 15 lamellar layers were prescribed in the resulting FE model. The mean stiffness for the experimentally tested IVDs was 423±35 N/mm intact, and 397±30 N/mm following nucleotomy. This difference of -5.8% between intact and nucleotomised IVDs was statistically significant ($P=0.042$, paired t-test). When no inter-lamellar slip was allowed in the FE simulations, the model predictions were within the range of experimental data, with a predicted stiffness of 416N/mm for the intact model, and 375N/mm for the nucleotomy model. However when inter-lamellar slip was allowed with a friction coefficient of 1.0, FE model compressive stiffness fell to 340N/mm, and when the friction coefficient was reduced to 0.0, the compressive stiffness reduced to 250N/mm.

Conclusions

Inter-lamellar shear resistance has a strong influence on the compressive stiffness of the intervertebral disc, with a change in interface condition from tied (no slip) to frictionless (no shear resistance) reducing disc compressive stiffness by 40%. However, it appears that substantial inter-lamellar shear resistance is present in the bovine tail disc. Decreases in inter-lamellar shear resistance due to degradation of bridging collagenous or elastic fibre structures could therefore be an important part of the process of disc degeneration.

References

Marchand & Ahmed 1990. Investigation of the laminate structure of lumbar disc annulus fibrosus. Spine 15:402-10.

Figures

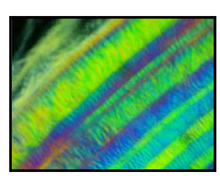

Fig1. Polarized light micrograph showing lamellar layers in bovine tail disc

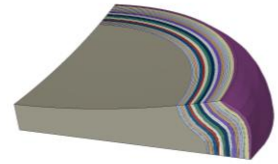

Fig2. FE model under 400N compression